ESSENTIALS OF Nanoscience & Nanotechnology

Narasimha Reddy Katta
Ph.D

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Chapter 1

INTRODUCTION TO NANOSCIENCE & NANOTECHNOLOGY

1.1. INTRODUCTION

Nanotechnology and Nanoscience are two areas that focus on matter at nanometer scale. Nanotechnology is very closely related to Nanoscience but obeys distinct drivers. Nanotechnology tries to respond to the particular needs while Nanoscience is primarily turned towards the discovery and study of novel phenomena and creation of new concepts to describe them. Both the fields are multi-disciplinary areas where knowledge of diverse areas such as physics, chemistry, engineering and biology are integrated.

1.2. NANOSCIENCE

Nanoscience is an emerging area of science which involves the study of materials on an ultra-small scale (nanoscale) and looks at the properties of nanoparticles. It is an interdisciplinary science, which means that it involves the concepts of more than one discipline, such as physics, chemistry, biology, medicine, materials science etc. In other words, Nanoscience prepares the way for a greater convergence of sciences into one single discipline.

1.2.1. Nanoscale

A Nanometer is a metric prefix and indicates a billionth of a part (10^{-9}). To give you some idea of the nanoscale, 10 hydrogen atoms laid side by side measure a nanometer across, a strand of DNA is 2.5 nm in diameter, while a red blood cell is about 7,000 nm wide, a human hair is between 50,000 and 100,000 nanometers thick, a biological cell is around 1,000 nanometers, while a pinhead size is around a million nanometers wide (Figure 1.1)

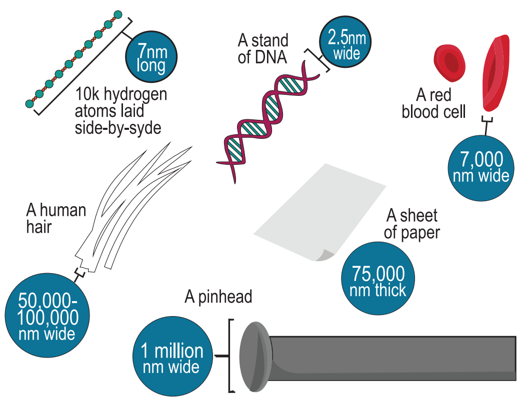

Fig.1.1. Size of a nanometer
(Source: Australian Academy of Sciences)

1.2.1. Nanoparticles

Nanoparticles are made up of a large number of atoms or molecules bonded with each other with total size varying from 1nm to around 100 nm. They serve as connecting links between molecular structures and macromolecules or bulk materials. Nanoparticles can be made of elements, organic molecules, inorganic compounds, inorganic cluster compounds or metallic/ semiconductor particles and many other biological materials. Nanoparticles have a high surface area to volume ratio which has dramatic effect on their properties compared to non-nanoscale forms of the same material.

1.2.3. Nanostructures

A nanostructure is a structure of intermediate size between microscopic and molecular structures. Nanostructural detail is microstructure at nanoscale. In describing nanostructures, it is necessary to differentiate between the number of dimensions in the volume of an object which are on the nanoscale. Nanotextured surfaces have one dimension on the nanoscale, i.e., only the thickness of the surface of an object is between 0.1 and 100 nm. Nanotubes have two dimensions on the nanoscale, i.e., the diameter of the tube is between 0.1 and 100 nm; its length can be far more. Finally, spherical nanoparticles have three dimensions on the nanoscale, i.e., the particle is between 0.1 and 100 nm in each spatial dimension. The terms nanoparticles and ultrafine particles (UFP) are often used synonymously although UFP can reach into the micrometer range. The term nanostructure is often used when referring to Nanotechnology.

Nanostructures are classified as carbon-based nanostructures (which include various low-dimensional allotropes of carbon including carbon black (CB), carbon fiber, carbon nanotubes (CNTs), fullerene, and graphene. CNTs, and graphene have very unique properties. CNTs can be categorized into semiconducting or metallic, organic based Nanostructures (Dendrimers, liposomes, micelles, polymer NPs, etc.), inorganic based Nanostructures, and composite based Nanostructures. Nanocomposites can be described as multiphase nanostructures with one phase.

Nanostructure materials could be defined as solids composed of structured elements mostly crystallites, with characteristic size (at least in one dimension) of few nanometers (<100). The advantage of these new materials is that they can be designed and built from atomic level upwards to have specific properties of great use to materials scientists. Nanocrystals may consist of over 1000 atoms but it can be quite variable within the 1-100 nm range. The wide applications of such nano-structures include semi-conductor devices, strained-layer lattices, and magnetic multilayers.

1.2.4. Nanomaterial

Nanomaterial is a general word for any material that has a composition based on nanoparticle units. Nanomaterials are usually considered to be materials with at least one external dimension that measures 100 nanometres or less or with internal structures measuring 100 nm or less. They may be in the form of particles, tubes, rods or fibers. Materials formed from nanoscale grains exhibit dramatic changes in their properties. By controlling the manner in which nanometer scale molecular structures are formed, it is possible to control the fundamental properties of the materials, such as colour, electrical conductivity, melting temperature, hardness, crack resistance and strength etc. Nanoscience strives to understand these changes and involves finding governing laws of these tiny objects, deriving theoretical models to describe the behavior of those nanoscale materials and analyzing the properties of them.

1.2.5 Definition of Nanomaterial

European Commission in 2011 defined "Nanomaterial" for regulatory purposes. According to it, if 50% or more of the constituent particles of a material in the number size distribution have one or more external dimensions in the size range 1 nm to 100 nm, then such material falls under the definition of Nanomaterial. The volume specific surface area (i.e., VSSA is equal to the sum of the surface areas of all particles divided by the sum of the volumes of all particles) can be used under specific conditions to indicate that a material is a Nanomaterial. VSSA > $60m^2/cm^3$ is likely to be a reliable indicator that a material is a Nanomaterial unless the particles are porous or have rough surfaces, but many Nanomaterials (according to the principal size-based criterion) will have a VSSA of less than 60 m^2/cm^3. The VSSA > 60 m^2/cm^3 criterion can therefore only be used to show that a material is a Nanomaterial, not vice versa. The VSSA of a sample can be calculated if the particle size distribution and the particle shape (s) are known in detail. The reverse (calculating the size distribution from the VSSA value) is unfeasible.

Two principal factors cause the properties of nanomaterials to differ significantly from other materials. One is increased relative surface area, and the other is quantum effects. These factors can change or enhance properties such as reactivity, strength and electrical characteristics. As a particle decreases in size, a greater proportion of atoms are found at the surface compared to those inside. For example, a particle of size 30 nm has 5% of its atoms on its surface, at 10 nm 20% of its atoms, and at 3 nm 50% of its atoms. Thus, nanoparticles have a much greater surface area per unit mass compared with larger particles. As growth and catalytic chemical reactions occur at surfaces, this means that a given mass of material in nanoparticulate form will be much more reactive than the same mass of material made up of larger particles.

Nanomaterials can be constructed by top-down techniques, producing very small structures from larger pieces of material, for example by etching to create circuits on the surface of a silicon microchip. They may also be constructed by bottom-up techniques, atom by atom or molecule by molecule. One way of doing this is self-assembly, in which the atoms or molecules arrange themselves into a structure due to their natural properties. Crystals grown for the semiconductors provide an example of self assembly, as does chemical synthesis of large molecules. Another way is to use tools to move each atom or molecule individually. This 'positional assembly' offers greater control over construction, but it is a laborious process.

1.2.6. Quantum Size effect

Quantum confinement is something which gives nano material its own unique identity. Quantum size effect occurs when the nanostructures themselve become smaller than a fundamental scale.

The properties of any material are essentially just the average of the quantum effects acting on those atoms. As the particle size is shrunk, eventually reaching nanosize, this averaging no longer works to describe the material's physical properties, and we must look at each individual atom's quantum behavior and their interactions with one another instead. This effect (also known as the quantum size effect) is due to a phenomenon known as confinement and is more prevalent in nanoparticles of 10 nm or less. It is well-known that particles can be described as acting like a wave or a particle.

In a bulk material, the electrons are generally treated as wave-like and are "free" to move between atoms. As we shrink the size of a particle, the spatial extent of electron wave-function is comparable to the particle's size, and the electron begins to "feel" the presence of particle boundaries and adjust their energy accordingly. In this way, electrons are now "confined" in quantized energy levels and the once freely-moving electrons are now restricted into these specific levels. Materials suddenly exhibit very different properties: opaque substances such as copper become transparent; stable materials such as aluminum turn out to be combustible; solids like gold become liquid at room temperature; and insulators such as silicon become conductors.

A powerful and fascinating result of quantum effects on the nanoscale is the concept of 'tunability'. By changing particle size, one can fine-tune a material's property of interest, such as changing the fluorescence color -

which can then be used to identify particles and label them with markers for various purposes. Quantum dots are one of the most significant developments which exploit such quantum tunability. They are nanoparticles lesser than 10 nm in size, made of semiconductor materials that have fluorescent properties. Their properties are closely related to their size and shape, and they lie between those of bulk semiconductors and discrete molecules.

1.3 NANOTECHNOLOGY

Nanotechnology is the creation of functional materials, devises and systems on nanometre length scale, exploiting novel phenomena and properties (physical, chemical and biological) present only at that nanoscale. In other words, it is collective term for a range of technologies, techniques and processes that involve the manipulation of matter at nanoscale. There are two approaches in nanotechnology known as top-down approach and bottom-up approach. Various concepts such as self assembly and molecular machines are also used in nanotechnology.

1.3.1. History of Nanotechnology

The concepts that seeded nanotechnology were first discussed in 1959 by renowned physicist Richard Feynman in his talk at an American Physical Society meeting at Caltech titled "There's Plenty of Room at the Bottom". He suggested that it should be possible to make machines at a nano-scale that "arrange the atoms the way we want".

In 1960 Mohamed Atalla and Dawon Kahang at Bell laboratories fabricated the first MOSFET (metal-oxide-semiconductor field effect transistor) with a gate oxide thickness of 100nm, along with gate length of 20μm. In 1962 they have also fabricated a monolayer base metal- semiconductor junction (M-S junction) transistor by using 10 nm gold thin films.

The term "Nano-technology" was first used by Norio Taniguchi of Tokyo Science University in his research paper (1974) in which he described nanotechnology as the processing of separation, consolidation, and deformation of materials by one atom by one atom.

Inspired by Feynman's concepts, K. Eric Drexler popularized the word 'Nano-technology' in the 1980's. He was talking about building machines on the scale of molecules, a few nanometers wide motors, robot arms, and even whole computers, far smaller than a cell. Drexler spent the next ten years describing and analyzing these incredible devices, and responding to accusations of science fiction.

Also, in 1986, Drexler co-founded 'The Foresight Institute' to help increase public awareness and understanding of nanotechnology concepts and implications. The emergence of nanotechnology as a field in the 1980s occurred through convergence of Drexler's theoretical and public work, which developed and popularized a conceptual framework for nanotechnology, and high-visibility experimental advances that drew additional wide-scale attention to the prospects of atomic control of matter. Since the popularity spike in the 1980s, most of nanotechnology has involved investigation of several approaches to making mechanical devices out of a small number of atoms. In 1980s, two major breakthroughs sparked the growth of nanotechnology in the modern era. One is the invention of Scanning Tunneling Microscope and other one is the discovery of Fullerenes.

The invention of the Scanning Tunneling Microscope in 1981 provided unprecedented visualization of individual atoms and bonds, and was successfully used to manipulate individual atoms in 1989. Gerd Binnig and Heinrich Rohrer of IBM-Zurich Research laboratory received Nobel Prize in Physics in 1986 for developing this micro-scope.

Fullerenes were discovered in 1985 by Harry Kroto, Richard Smalley, and Robert Curl, who together won the 1996 Nobel Prize in Chemistry. C60 was not initially described as nanotechnology; the term was used regarding subsequent work with related graphene tubes (called carbon nanotubes and sometimes called Bucky tubes) which suggested potential applications for nanoscale electronics and devices. The discovery of carbon nanotubes is largely attributed to Sumio Iijima of NEC in 1991, for which Iijima won the inaugural 2008 Kavli Prize in Nanoscience.

In the early 2000s, the nanotechnology field garnered increased scientific, political, and commercial attention that led to both controversy and progress. Controversies emerged regarding the definitions and potential implications of nanotechnologies, exemplified by the Royal Society's report on nano-technology. Challenges were raised regarding the feasibility of applications envisioned by advocates of molecular nanotechnology, which culminated in a public debate between Drexler and Smalley in 2001 and 2003.

1.3.2. Larger to smaller : a materials perspective

One of the fundamental concepts which is the ground basis for nano science or nanotechnology is the material perspective. Before the advent of nanotechnology material was not seen atomically. Scientists started decomposing large materials to form new components from them. It has been observed that decomposition of materials at nano scale changes its properties.

A number of phenomena become pronounced as the size of the system decreases. These include statistical mechanical effects, as well as quantum mechanical effects, for example the "quantum size effect", where the electronic properties of solids are altered with reductions in particle size. This effect does not come into play by going from macro to micro dimensions. However, quantum effects can become significant when the nanometer size range is reached, typically at distances of 100 nm or less (the so-called quantum realm). Additionally, a number of physical properties change when compared to macroscopic systems. One example is the increase in surface area to volume ratio altering mechanical, thermal and catalytic properties of materials. Diffusion and reactions at nanoscale, nanostructure materials and nano-devices with fast ion transport are generally referred to nano-Ionics. Mechanical properties of nano-systems are of interest in the nanomechanics research. The catalytic activity of nanomaterials also opens potential risks in their interaction with bio-materials.

Materials reduced to the nanoscale can show different properties compared to what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances can become transparent (copper); stable materials can turn combustible (aluminum); insoluble materials may become soluble (gold). A material such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nano-technology stems from these quantum and surface phenomena that matter exhibits at the nanoscale.

1.3.3. Simple to complex : a molecular perspective

Advanced chemistry has reached the level where it can produce molecules for almost every structure of the present world. These techniques are used to prepare a wide range of chemical compounds such as polymers and pharmaceuticals but the extension of the control gives birth to the question that how these molecules could be reassembled into more advanced super molecular assemblies. Molecular self assembly is gradually evolving into supramolecular chemistry to make the new components which can reassemble themselves. The concept of molecular recognition is especially important: molecules can be designed so that a specific configuration or arrangement is favored due to non-covalent intermolecular forces. The Watson–Crick base pairing rules are a direct result of this, as is the specificity of an enzyme being targeted to a single substrate, or the specific folding of the protein itself. Thus, two or more components can be designed to be complementary and mutually attractive so that they make a more complex and useful whole.

Such bottom-up approaches should be capable of producing devices in parallel and be much cheaper than top-down methods, but could potentially be overwhelmed as the size and complexity of the desired assembly increases. Most useful structures require complex and thermodynamically unlikely arrangements of atoms. Nevertheless, there are many examples of self-assembly based on molecular recognition in biology, most notably Watson–Crick basepairing and enzyme-substrate interactions. The challenge for nanotechnology is whether these principles can be used to engineer new constructs in addition to natural ones.

1.3.4. Molecular Nanotechnology

Molecular Nanotechnology is defined as the technology which is used for engineering the mechanical or functional machines at molecular scale or we can say machines having atom by atom arrangement are known as molecular machines. Its concept has originated in 1992 when a panel of researchers were exploring the diversity of nanotechnology. Usually molecular nanotechnology is abbreviated as MNT. This is one of the most advanced forms of nanotechnology which is used to manufacture the machinery at miniature level. MNT would involve the physical demonstration of the existing principles of chemistry and physics.

1.3.5. Nanomechanics and Bio materials

The concept of nanomechanics was also originated when new chemical properties of conductors and semi conductors were found. Nanomaterials empowered the production of new devices but at the same time it also opened the potential risks in their reactions with biomaterials. Materials exhibit different properties as they exhibited at macro level which enabled unique applications to take place. For example opaque elements become transparent such as copper, insulators become conductors at nano scale, solid can be converted into liquid at normal room temperature such as gold. Bottom line is that nanotechnology totally transformes the entire structure of any substance into new architecture.

1.4. DIMENSIONALITY IN NANOMATERIALS

The first classification idea of Nano Structured Materials (NSM's) was given by Gleiter in 1995 and was further explained by Skorokhod in 2000. However, Gleiter and Skorokhod scheme was not fully considered because of 0D, 1D, 2D, and 3D structures such as fullerenes, nanotubes, and nanoflowers were not taken into account. In the last decade hundreds of new NSMs and abundance of novel nano-structures (NSs) have been obtained so the need in their classification has ripened. Therefore, Pokropivny and Skorokhod reported a modified classification scheme for NSMs, in which 0D, 1D, 2D and 3D NSMs are included. Crucial to this classification is the concept of confinement, which may be roughly interpreted as a restriction in the ability of electrons to move in one or more spatial dimensions.

Zero dimensional (0D): Zero dimensional materials are Materials wherein all the dimensions are measured within the nanoscale (<100nm). The most common representation of zero-dimensional nanomaterials are nanoparticles.

Nanoparticles can be amorphous, single crystalline or polycrystalline, composed of single or multi-chemical elements, they exhibit various shapes and forms and exist individually or incorporated in a matrix. They can be metal, semiconductor, fullerene uniform particles arrays (quantum dots), hetero-geneous particles arrays, core shell quantum dots, hallow spheres and nano lenses.

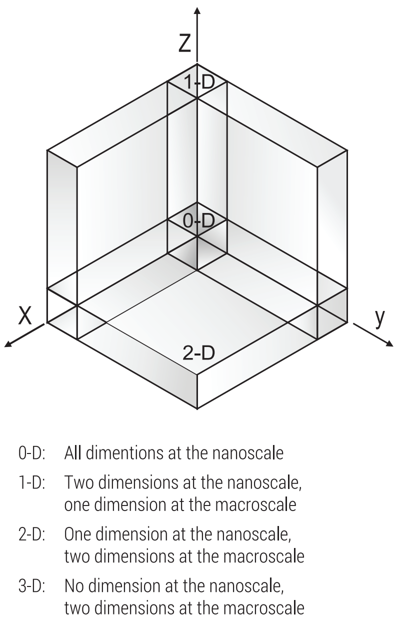

Fig. 1.2. Classification of nanoscale dimensions.
(Source: Tallinn University of Technology)

One dimensional (1D): one dimension is outside the nanoscale. This leads to needle like-shaped nanomaterials. They can be amorphous or crystalline, standalone materials or embedded within another medium, metallic, ceramic, or polymeric such as nanotubes, nanorods, and nano wires.

Two dimensional (2D): Two of the dimensions are not confined to the nanoscale and are considered to be thinnest nanomaterials due to their thickness and dimensions on macro/nanoscale. 2D nanomaterials include nanofilms, nanolayers, and nano-coatings. They can be amorphous or crystalline made up of various chemical compositions. These are deposited as single layer or as multilayer structures deposited on substrates, integrating in surround matrix material. They can be metallic, ceramic, or polymeric, with strong bonds and weak Vander Waals between layers.

Three dimensional(3D): Bulk materials are materials that are not confined to the nanoscale in any dimension. These materials are thus characterized by having three arbitrary dimensions above 100 nm. These materials possess a nano-crystalline structure or involve the presence of features at the nanoscale. In terms of nanocrystalline structure, bulk materials can be composed of multiple arrangements of nanosize crystals, most typically in different orientations. With respect to the presence of features at the nanoscale, 3D nanomaterials can contain dispersions of nanoparticles, bundles of nanowires, and nanotubes as well as multinanolayers.

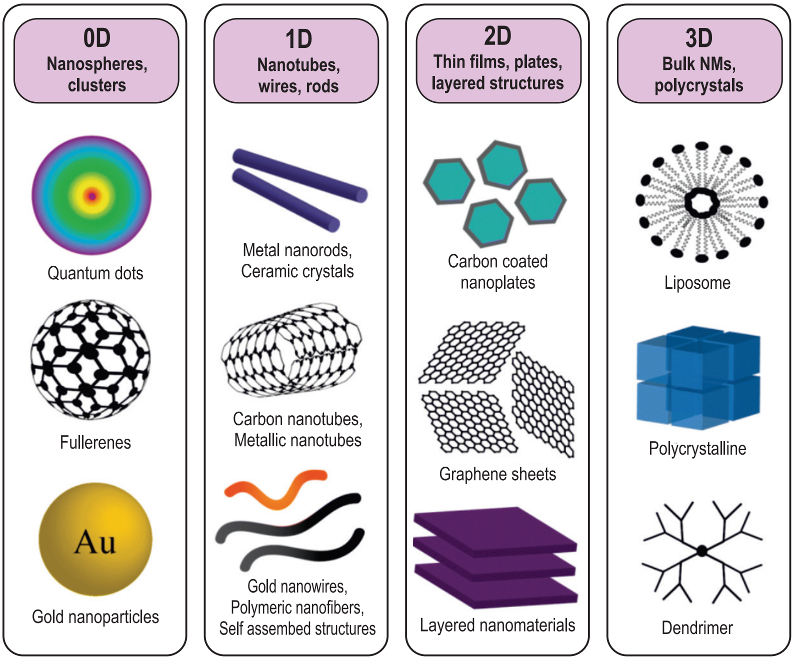

Fig. 1.3. Nanomaterials classification based on dimensionality (Source: Tuang Yeow Poh)

1.5. INORGANIC, ORGANIC AND BIOLOGICAL NANOMATERIALS

Broadly, we can categorize nanomaterials into different groups namely organic, inorganic and biological (but it is possible to have a hybrid inorganic-organic nanoparticle too).

1.5.1. Organic Nanomaterials

Organic nanomaterials are compounds containing the element carbon (and often hydrogen too which forms hydrocarbons). Organic nanomaterials include carbon (except fullerenes), polymeric and lipid based nanocarriers. Recent advances enable researchers to create organic nanomaterials with specific atoms, geometries and electronic arrangements. Several different types of organic nanostructures are being tested as potential building blocks. Liposomes Den-drimers, Carbon nanomaterials and Polymeric NP, Micelles are some of the organic nanomaterials (Figure 1.4)

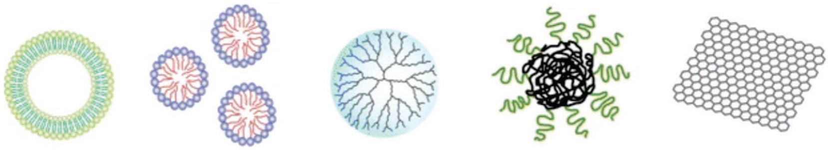

Fig. 1.4. Organic nanomaterials

Liposomes and polymeric nanomaterials protect drugs against in vitro and in vivo degradation, allow drug release in a controlled manner, and may also be designed for drug targeting. Liposome are one of the first nanostructures having desired physico chemical properties with desired physico chemical properties that, by exploiting a combination of a number of suitable soft interactions, can facilitate the transit through the biological barriers from the point of administration up to the site of drug action.

Dendrimers are highly branched synthetic polymers, star shaped macromolecules with nanometer scale (<15nm) dimensions. Dendrimers are defined by three components: a central core, an interior dendritic structure (the branches), and an exterior surface with functional surface groups. The varied combination of these components yield products of different shapes and sizes with shielded interior cores that are ideal candidates for applications in both bio-logical and materials sciences. While the attached surface groups affect the solubility and chelation ability, the varied cores impart unique properties to the cavity size, absorption capacity, and capture-release characteristics. Their application includes drug delivery, catalysis, gene - transfection, energy harvesting, photo activity, molecular weight and size determination, rheology modification, and nanoscale science and technology.

Carbon nanotube, also called buckytube is a nanoscale hollow tube of carbon atoms. The cylindrical carbon molecules feature high aspect ratios (length-to-diameter values) typically above 103, with diameters from about 1 nanometer up to tens of nanometers and lengths up to millimeters (Figure 1.5).

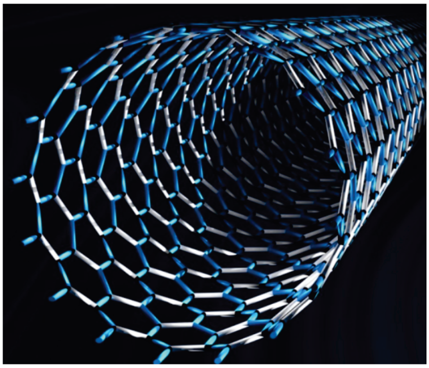

Fig.1.5. Carbon nanotubes

This unique one-dimensional structure and concomitant properties endow carbon nanotubes with special natures, rendering them with unlimited potential in nanotechnology-associated applications. Carbon nanotubes are members of the fullerene family.

1.5.2. Inorganic Nanomaterials

The term Inorganic Nanomaterials describe nanostructures in which carbon is not present and combined with some other elements. These NM are stable, robust, resistant, highly functional. and are quite easily cleared from the body. Furthermore, inorganic material exhibit truly exciting mechanical, optical, physical and electrical phenomena at the nanoscale which can be tailored through changes in material, phase, shape, size and surface characteristics. Oftentimes, it is necessary to add a biocompatible surface to inorganic nanoparticles to avoid toxicity, especially for heavy metals.

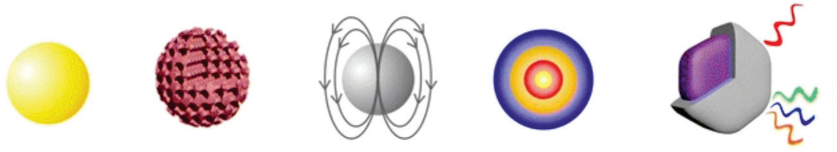

Fig.1.6. Inorganic nanomaterials

Inorganic nanoparticles cover a broad range of substances including elemental metals, metal oxides, and metal salts.

Fig.1.7. Metallic nanoparticles, nanospheres and Nanoshells
(Source: Research gate)

Silver nanoparticles (AgNPs) are used in many products as a bactericide, whereas gold nanoparticles (AuNPs) are explored for many possible applications because of their catalytic activity. Both silver and gold nanoparticles possess the so-called surface plasmon as a result of the collective oscillation of the electrons, which gives them excellent optical properties and a large enhancement of the electric field on their surface.

Quantum dots (QDs) are semiconductor nanocrystals with all three dimensions falling in the 1–10 nm size range. In many respects, these luminescent nanocrystals constitute a transitional stage between bulk semiconductors and single atoms. The QD core is made up of elements from the II–VI (e.g., CdSe, CdTe, CdS, and ZnSe), III–V (e.g., InP and InAs), or IV–VI (e.g., PbSe) group. They have aroused widespread interest by virtue of their exceptional optical, electronic, electrochemical, photophysical, redox, and catalytic properties.

Nanoparticulate metal oxides are widely used, such as TiO_2, Al_2O_3, ZrO_2, MnO_2 and CeO_2, as well as nanoparticles of iron oxides (FeOx). Attention should be paid to the increasingly used magnetic nanoparticles, which have been synthesized with a number of different compositions and phases, including iron oxides, such as Fe_3O_4 and γ-Fe_2O_3, pure metals, such as Fe and Co, and spinel-type ferromagnets, as well as alloys. Moreover, silica nanoparticles (SiO_2) are characterized by presenting high surface areas and exhibit intrinsic surface reactivity, which allows chemical modifications.

Nano-size zeolite, clays, and ceramics are other nanoparticles that have been proposed for various applications.

1.5.3. Biological & Hybrid nanomaterials

Hybrid nanomaterials that contain organic components (organic groups or molecules, ligands, biomolecules, pharmaceutical substances, polymers, etc.) and inorganic components (metal ions, metal clusters or particles, salts, oxides, sulfides, non-metallic elements and their derivatives, etc.) play a paramount role in contemporary research. Advanced molecular architectures based on hybrid nanomaterials admittedly provide an outstanding driving force for the active progress in several research areas, including the development of new platforms for drug delivery, smart and stimuli-responsive materials, sensors, as well as nanomedicine, industrial technologies, material sciences, and energy applications.

Linking organic molecules to metal nanoparticles may create highly reactive hybrid organic–inorganic systems. Despite the short lifetime of such nanostructures, they ensure facile chemical activation of organic molecules. Their key applications arise in the fields of catalysis and organic synthesis, where nanomaterials are currently promoting a new wave of highly active and selective catalyst development.

Biological systems provide a rich range of examples of specialized chemical systems that are structured on the nanoscale. Nanofibres, microtubules, viruses, and ribosomes are examples of systems that can be studied from the perspective of nanoscience. Using these systems or developing artificial systems which mimic their functionality are important growth areas in nanoscience.

1.6. SOCIETAL IMPLICATIONS OF NANOTECHNOLOGY

The societal impact of nanotechnology are the potential benefits and challenges that the introduction of novel nanotechnological devices and materials may hold for society and human interaction. The societal impacts of new technologies are easy to identify but hard to measure or predict.

Technology has always been a double-edged sword, and that is certainly true of nanotechnology. The same technology that promises to advance human health and wealth also has the potential for destructive applications. Nanotechnology has many advantages, it provides new answers and solutions to the field of medicine, technology, and fiction sciences but at the same time, it has spread a questionable influence on the safe and clean drinking water, reliable energy, clean air and education. Protection of environment and heath care have become a challenge for human race. In this scenario, proper and periodic regulation of nanotech manufacturing plants is needed. It should be kept in mind that to what extent the world can afford the damage it caused. People should be educated about the applications of nanotechnology and its side effects.

A high proportion of nanotechnology research is focused towards military applications. The potential military applications include nanorobotics, magnetorheological fluid (MRF), artificial intelligence and molecular manufacturing. The enhancement of military application in nanotechnology may thus indirectly increase the occurrence of terrorist attacks in the future. The advanced developments in the military technology may have implications for societal and political relations within the community. Modern defense armies are protected from today's civilian threats in a way that never had before. It is likely that nanotechnology will further widen the gap between the means of political violence available to the military and those available to the civilian population